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4-kW multi-phase battery powered power supply

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Abstract. A method was developed for building the powerful battery power supplies. Using the method, the battery power supply with a 4 kW max power and up to 93% efficiency was developed to supply the “Yasen” X-ray apparatus. Two 60 A·h series-connected starter lead-acid batteries were used as a primary power supply. A DC output voltage of the source is stable over the entire power range and equals to 310 V. The power supply is based on a 5-phase HF-inverter. There is no difficulty in designing such power supplies with different power outputs. It can be done by the increasing or the decreasing number of phases (of inverter channels). This approach is not limited by the increased number of the inverter channels. The maximum output power will be determined by the battery characteristics only. The power supply is mounted on a mobile trolley, to increase the mobility of the entire set of equipment. The unit dimensions are 410x320x440, the weight is about 40 kg. The unit is forced air-cooled. A power operating mode is short and periodic.

1. Introduction

The self-contained power supplies are commonly used to power various electrical installations and devices in case the connection to the mains is not available. These are divided into two main types – the electromechanical and the battery powered power supplies. The electromechanical power supply is an electric power generator driven by a combustion engine. A release of harmful substances from the engine into the atmosphere reduces the scope of its application. Furthermore, this type of devices does not provide even a short-time increase in the power taking off that exceeds an average value. In contrast to the electromechanical power sources, the battery powered power supplies are more environmentally friendly and allow a short-time high power output. However, a limited capacity of the battery, and hence the energy stored, does not allow supply of the high power equipment within an extended period

This paper describes a design, an operating principle, and the characteristics of the 4 kW battery powered supply intended for the “Yasen” X-ray apparatus [1].

It should be noted that the market offers a large variety of the battery powered power sources of various capacities produced by Russian and foreign manufacturers. Initially, attempts were made to use these units to provide feeding of the “Yasen” X-ray apparatus. However, these attempts were not successful due to the requirements specified to the X-ray apparatus power supply. All the employed units are fed with the 220-volt AC household electrical equipment or the electro-driven tool, which is not sufficiently sensitive to a decrease of the supply voltage. Thus, the power supplies =12/~220 V made both by Russian and foreign manufacturers demonstrated a significant output voltage reduction at the maximum rated power. As a result, those were not appropriate to power the “Yasen” X-ray apparatus, which requires a stable supply voltage over the entire range of the rated input, since the magnetic compressor included in the circuit is sensitive to the supply voltage.

2. Problems occurring during development of powerful low-voltage power supplies

Lead-acid car starter batteries are most often used as a primary power source in the powerful self-contained power supplies. The output voltage of these batteries is 12 V. The study revealed that the output power of the device with a single 60 A·h battery is limited by about 2–3 kW. This is due to the fact that under loading the battery output voltage reduces. The reducing depends on the state of charge, capacitance, the charge level of the battery, and other factors. A high-ampere current flowing through a primary electric circuit causes a voltage drop across its components, which results in a further decrease of the voltage supplied to the high-frequency transistor inverter, which is an integral part of these devices. In addition, we should consider the voltage drop across the inverter transistors: as the current flowing through the circuit grows, it increases. Due to low supply voltage of the inverter (several volts), the filtering capacitance becomes ineffective. In this case, the pulsed power taking off occurs mainly from the battery. Additional losses in the circuit are caused by the skin effect occurring in conductors. Thus, as the output power grows, the supply voltage of the transistor inverter decreases, and the voltage drop across the transistors increases. This leads to a vicious circle, when the supply voltage drop requires an increased current input. The increased current input leads to the further reduction in the circuit voltage supply.

The power of the supply can be increased up to 4 kW or higher by increasing the supply voltage via two 12 V series-connected batteries. However, even in this case the primary circuit current reaches 200 A at maximum output power. The current flow of this magnitude poses special requirements for the high-frequency transistor inverters. Though, there are semiconductor devices with a similar operating current level, however, the single transistor inverter, in this case, was not effective. We propose to use a multi-phase inverter transistor. It should be noted that the idea is not innovative, and it is widely used to provide a computer processor power supply. Microchips to control this type of high-current low-voltage inverters are produced by a number of leading companies. Also, the multiphase power supplies with a battery backup exist. A 1 kW unit developed by Orchid Technologies is presented in Orchid Technologies leaflet (http://orchid-tech.com/wp-content/uploads/2014/12/ OTEC_Design_Note_90_web.pdf). The multi-phase two-kilowatt high-voltage regulated power supply for space applications is described in [2].

3. Design description

The block diagram of the device is shown in Figure 1. The main component of the system is a 5-phase inverter. It consists of 5 similar transistor inverters made in accordance with a push-pull circuit. The maximum output power of every inverter is up to 800 W. The development and design costs of the inverter of this power level are significantly lower than those in the case of a single 4 kW inverter.

The control system generates on/off signals for the inverter transistors. In addition, the control system measures the output voltage and the inverter current input during operation and ensures the device protection. The control circuit also provides a number of service functions and indication of the operating modes. A 32-bit STM32F030C8 controller is used to perform measurement, control, and protection.

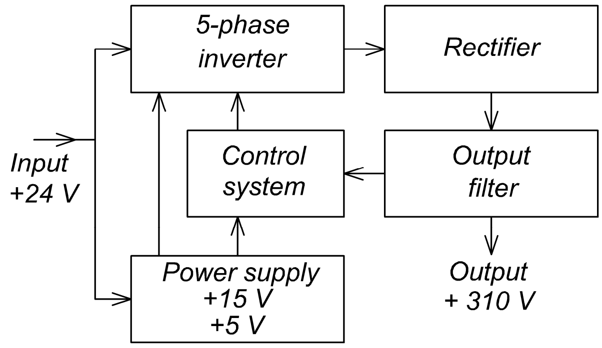

Figure 1. The block diagram of the device.

The CPLD EPM240T100C5N is used to control the inverter. This microchip receives a 7 bit binary control signal from the microcontroller and generates 5 pairs of output pwm-signal sequences. The output signals are displaced in phase by 3600/5=720. The diagrams of the control and output signals are shown in Figure 2. The data were obtained through CPLD operation simulation using Quartus 9 software. During simulation, the input values from the microcontroller were being increased and the duration of the transistor control pulses was growing.

Figure 2. Results of EPM240T100C5N simulation.

Input signals f1[0:6] are fed by the microcontroller and carry a binary code information on the value of the inverter transistors turn-on angle. The ena signal is an enabling signal for five pairs of the ph1 ph5 control signals to travel to the inverter transistors. The diagram shows when the control pulse width increases, at a certain point, one of the inverter transistors keeps open. This means that the current from the battery is continuously fed by switching between the inverters. The output frequency of the device is 5 times greater than the inversion frequency (5*33 kHz=165 kHz). The increased frequency of the output voltage reduces the requirements to the output filter.

An auxiliary power unit is used to provide +5 V for the control system and +15 V to power the inverter drivers. The power supply is simple in its structure; it is made of standard components forming a step-down circuit.

4. Experimental results

The results of the power supply testing are shown in Figure 3. The values of the power consumed by the "Yasen" apparatus at different operating frequencies are plotted along the X axis. The Y axis indicates the values of the device efficiency, voltage U_b and battery current I_b. The currents were measured by standard shunts with 0.5 accuracy class. M381 pointer-type ammeters of 1.5 accuracy class were used as indicators in current measurement. The voltage was measured with digital devices MY-62. The output voltage of the unit remained stable and was equal to 310 V over the entire operating range. The output voltage of the power supply started to decrease at an operation output power above 4.3 kW. At this power the operation frequency of "Yasen" apparatus was 3.5 kHz. The power supply attained its maximum power efficiency of 93% at 4.1 kW. A further increase in the

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power input caused the efficiency drop, and the output voltage was observed to decrease. The device efficiency at a low output power level was found to be below the maximum, as well. One of the causes of this phenomenon is that the losses, occurring during the reversal magnetization of the transformer cores and the switching losses in semiconductors, are virtually stable over the entire range of the output power. However, in the low output power range, their impact on the efficiency is more significant. Furthermore, in the high-power range, the battery current is not fed by pulses, but continuously due to the phase shift. This cancels out the skin effect, which is equivalent to the reduction of the ohmic losses in the primary high-current circuit. The duration of the "Yasen" apparatus operating during all the measurements was equal to 2 s.

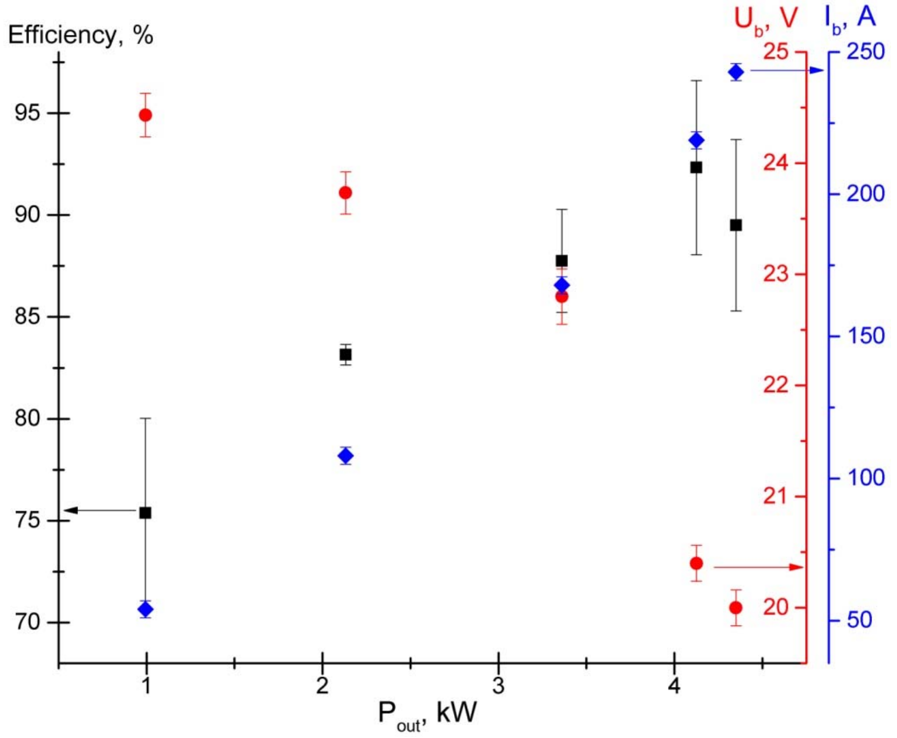

Figure 3. The results of the power supply testing.

The power supply is mounted at a mobile trolley to increase the mobility of the entire equipment set. The unit dimensions are 410x320x440, the weight is about 40 kg. Lithium-ion batteries can be used instead of lead-acid ones, to reduce the power supply dimensions and weight. The unit is forced air-cooled. The power operating mode is short and periodic.

5. Discussion and conclusion

Findings of the research demonstrate the possibility of designing a battery pack in accordance with the proposed approach. It should be noted that the constructed and tested prototype is only an experimental setup. The authors suggest that an optimization of the device can improve its efficiency. The optimization is possible through both the changed number of the inverter channels (phases) and an additional circuitry and design solutions. The reduced number of channels decreases the switching losses since the total number of transistors and transformers in the inverter reduces. However, the increased current loading per every channel increases the conduction losses. To design an effective device, a study is to be conducted to find the optimum number of the inverter channels in every case. The decreased operating frequency of the inverter will also reduce the switching losses.

Further enhancement of the device efficiency is possible by optimizing a technique of the residual energy recuperation. The residual energy is the energy stored in the transformer cores of the inverter and conductors at the time of the current flowing through the inverter transistors. In our circuit, this energy is stored in an intermediate capacitor and then transferred back to the primary power source through the power resistor. The Joule's losses in the resistor can be significantly reduced by its replacing with an active circuit of the residual energy recuperation. An active recuperation circuit can be a separate high-frequency inverter to transform the energy from the intermediate capacitor to the primary power supply.

The design and parameters of the inverter transformers are also important targets for a device optimization. The topology of power conductors should also be considered when designing this type of device.

The proposed approach can be readily used as a basis for creating the powerful battery power supplies in a wide range of capacities for various applications.

References

[1] Bessonova V A, Gavrilov P V, Komarskiy A A, Korzhenevskiy S R and Chepusov A S 2016 *Medical Radiology and Radiation Safety* **2** pp 53-57

[2] Garth D R, Muldoon W J, Benson G C and Costague E N 1971 *Power Electronics Specialists Conf. (Pasadena, CA)* vol 1 (New Jersey: IEEE) pp 110-16